VERITAS Observations of Supernova Remnants

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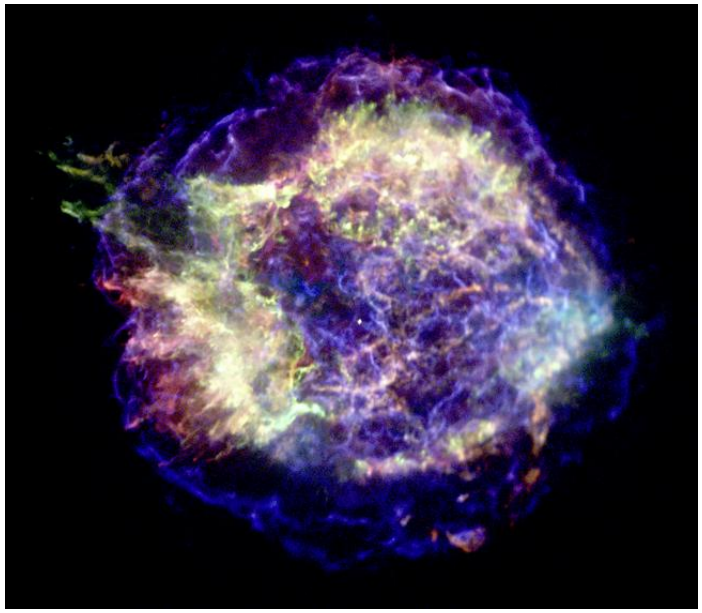
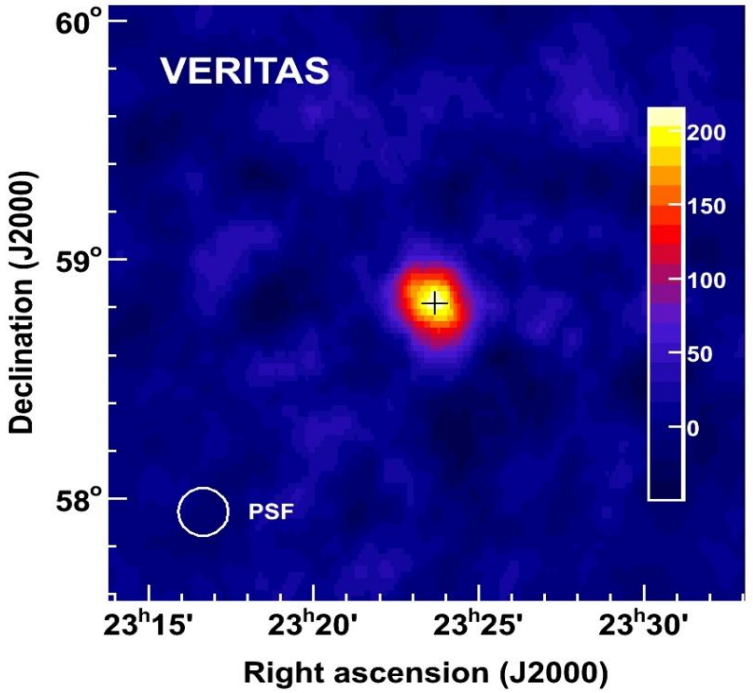
THE VERITAS Observatory

- Four 12m-diameter Imaging Atmospheric Cherenkov Telescopes
  - Located at Whipple Observatory Base Camp (altitude: 1300 m)
  - Full operations began Fall, 2007
  - ~1000 Hours of Observation time per year (including 200+ hrs in moonlight)

Cas A



Credit: NASA/CXC/MIT/UMass Amherst/M.D.Stage et al.

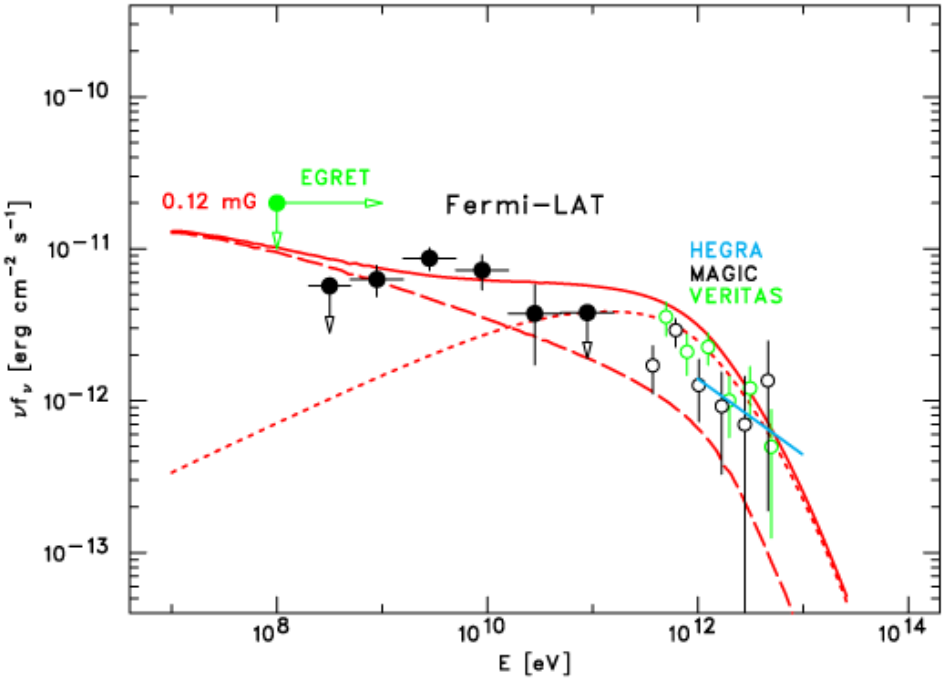


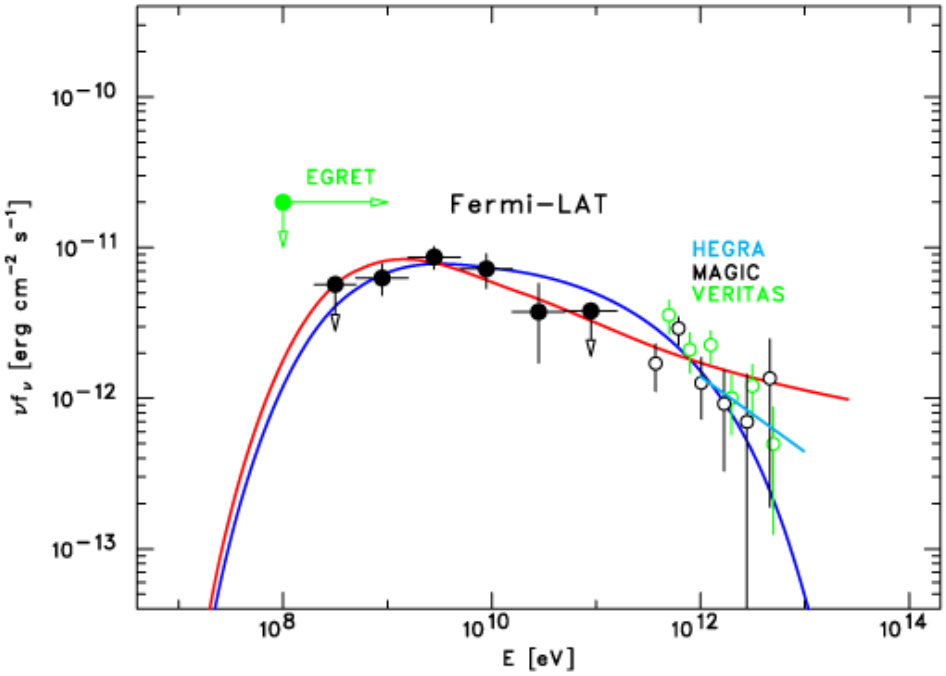
- Young (~330 yr) shell-type SNR
- VERITAS Detection:
  - 22 hours of data (2007), 8.3 σ
  - Consistent with point source
  - Index: $2.61 \pm 0.24_{stat} \pm 0.2_{sys}$ – no evidence for cutoff
  - Flux (> 1 TeV) ~3.5% Crab

Acciari et al. ApJ 714 (2010)

Cas A

- Modeling from Fermi-LAT Team:





Leptonic Model

B=120μG, PL (-2.34) + cutoff @ 40 TeV
Dashed Line – Brem
Dotted Line – IC (dominated by FIR)

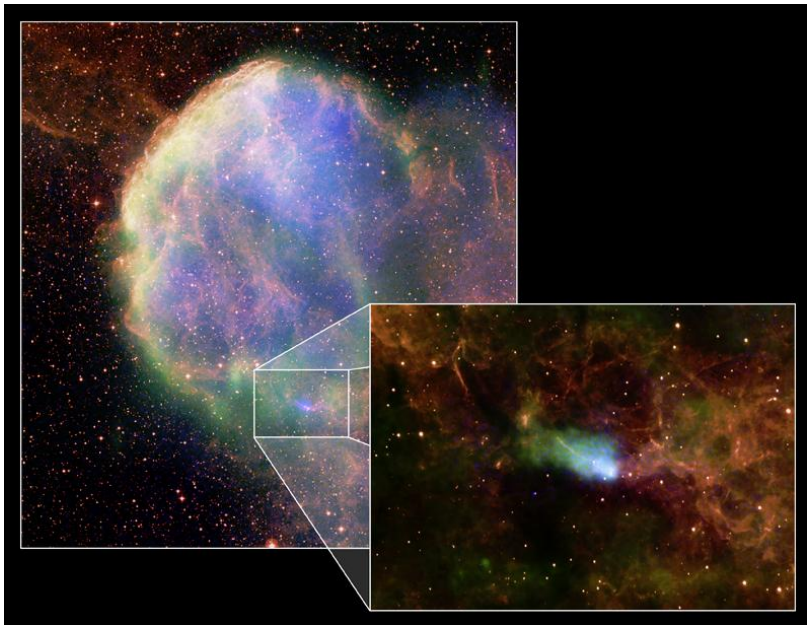
Hadronic Models

Blue: PL (-2.1) + cutoff @ 10 TeV
Red: PL (-2.3)

Hadronic model is favored, but leptons not ruled out

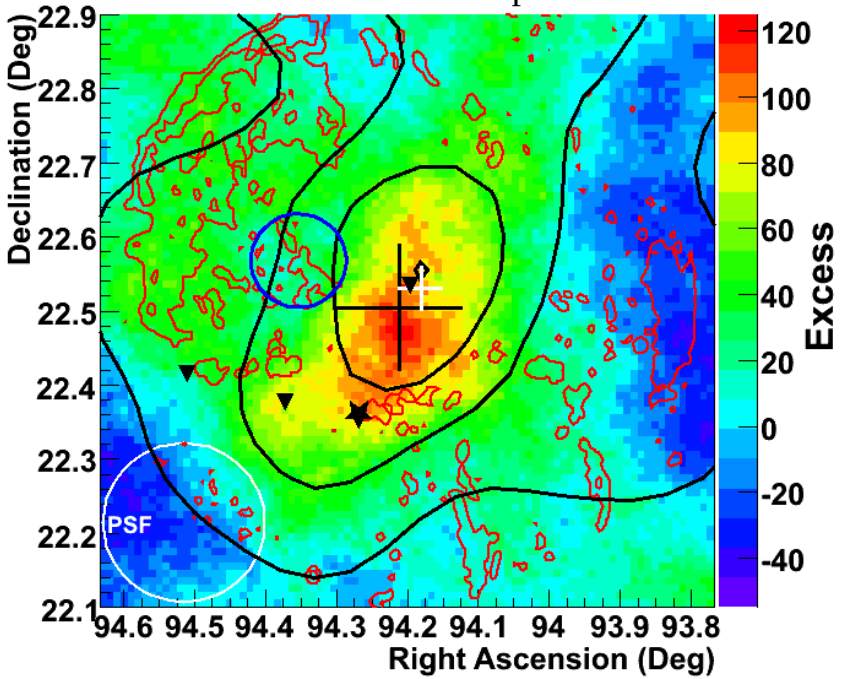
Abdo et al. ApJL 710 (2010)

IC443



Credit: Chandra X-ray: NASA/CXC/B.Gaensler et al; ROSAT X-ray: NASA/ROSAT/Asaok
Radio Wide: NRC/DRAO/D.Leahy; Radio Detail: NRAO/VLA; Optical: DSS

TeV Excess Map



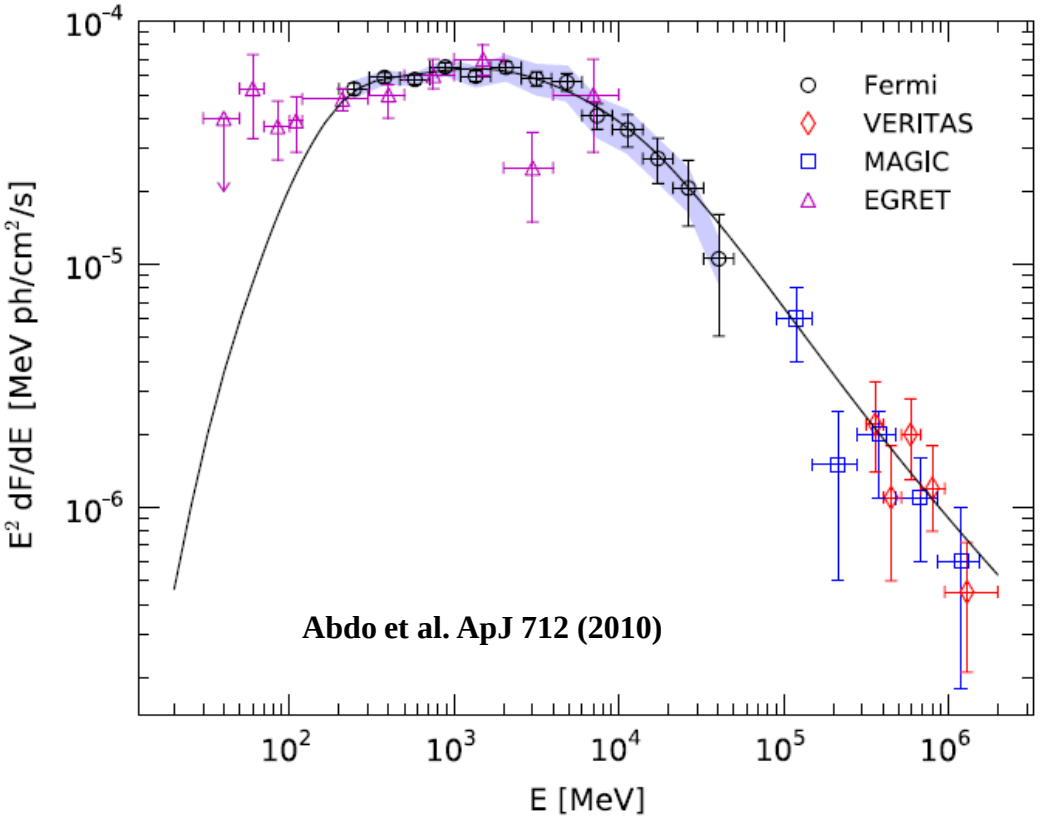
- Older (~20-30 kyr) radio/x-ray bright SNR
- PWN and likely SNR / MC Interaction (masers)
- Co-Discovery in TeV by VERITAS (2007)
  - 38 hrs, 8.3σ, 3.2% Crab (> 300 GeV)
  - Index: $2.99 \pm 0.38_{stat} \pm 0.3_{sys}$
  - Emission is extended ~ 0.16 deg.

Black: CO Contours
Red: Optical
Blue: 0FGL Source
Triangles: Masers
Star: PWN

Acciari et al. ApJL 698 (2009)

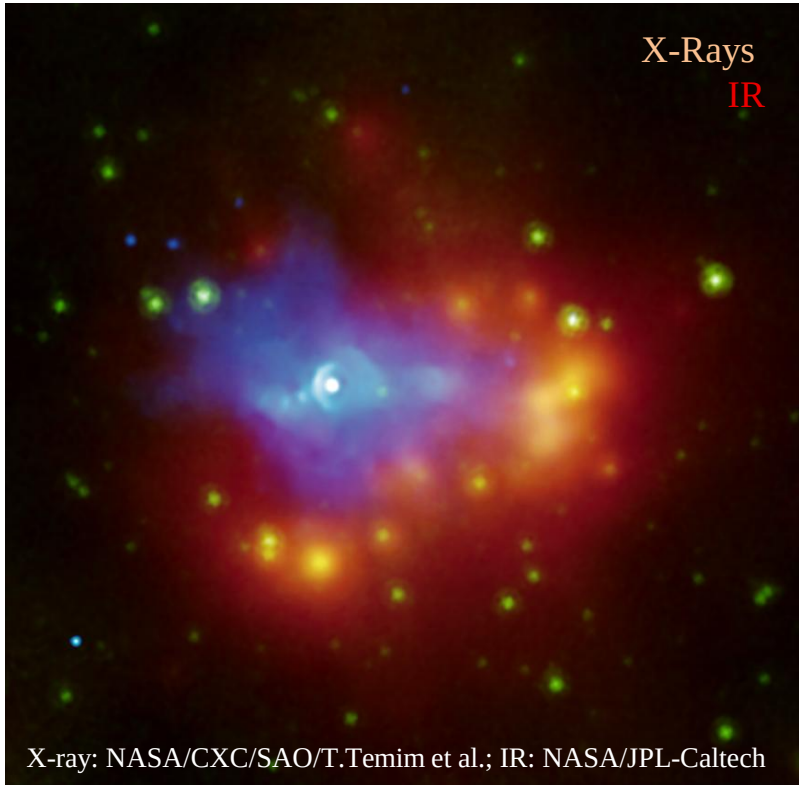
IC443 II

- Fermi Observations, 5-50 GeV
  - Location consistent with VERITAS
  - Angular Extent ~ 0.27 deg
- Hadronic Model
  - Proton population with broken power law spectrum (70 GeV breakpoint)
  - 10^4 Solar Masses of target material

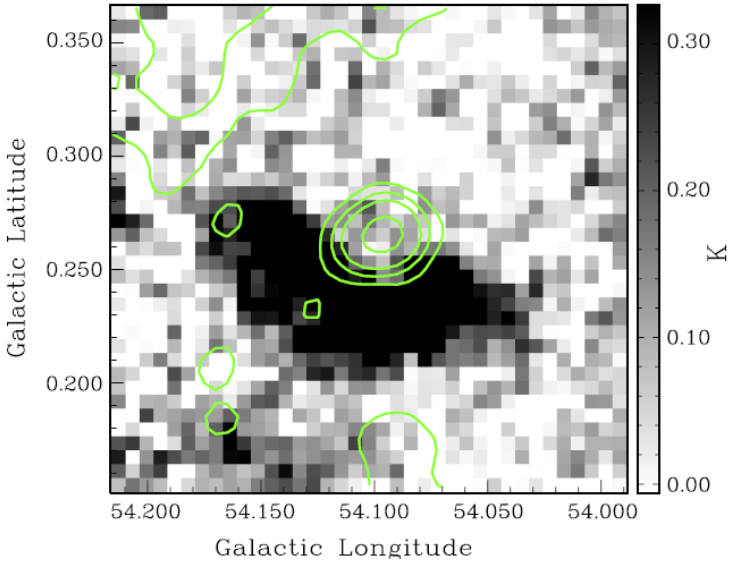


G54.1+0.3: Motivations

- "Cousin of the Crab"
  - X-ray jet/torus, IR dust shell
  - Age ~ 2900 years
  - E-dot = 1.2×10^{37} erg/s
  - Distance ~ 6.2 kpc



- Also, Nearby Molecular Cloud:

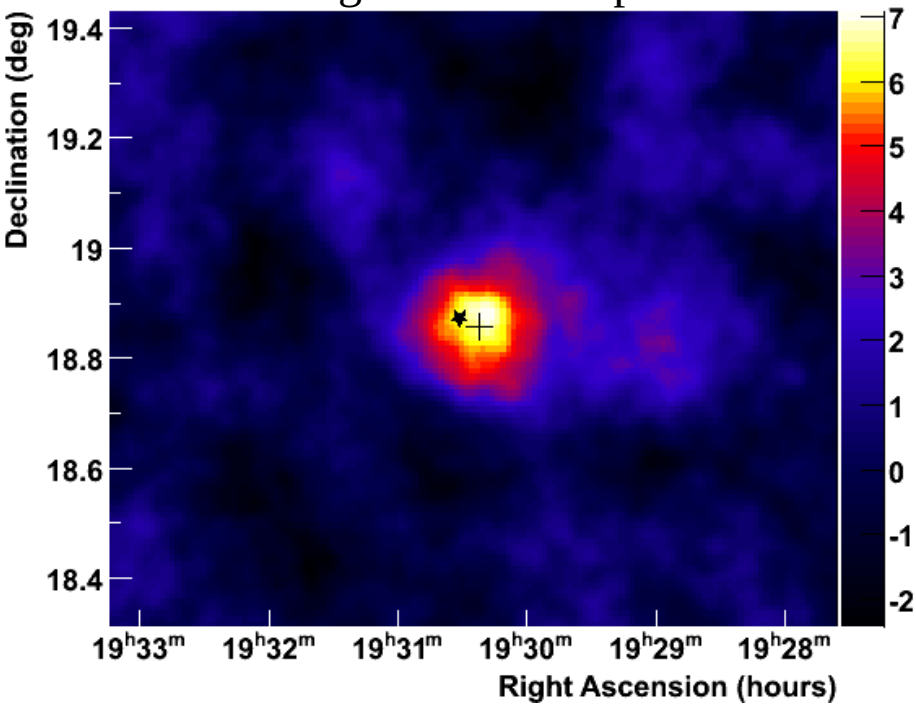


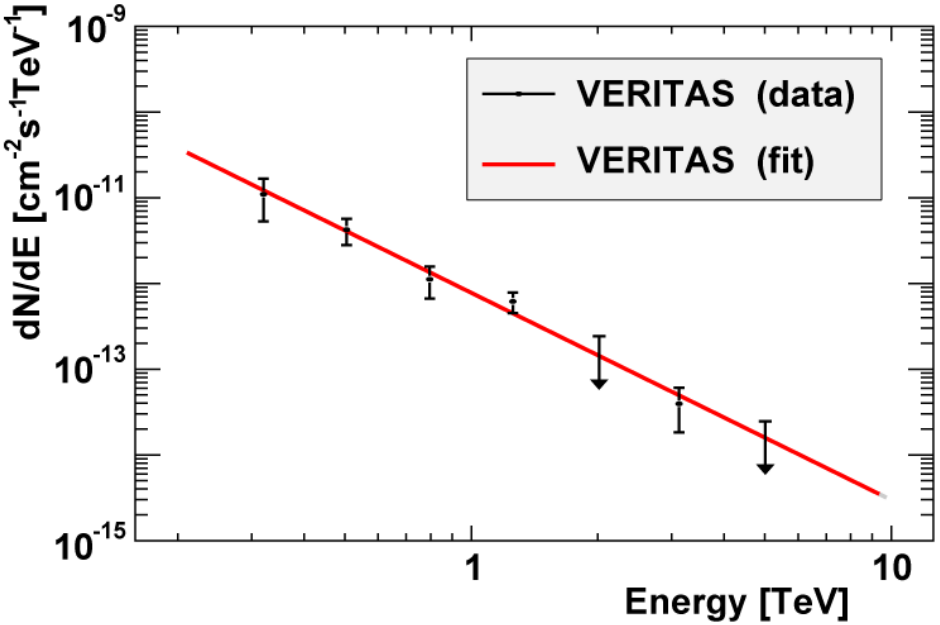
Leahy et al. (FCRAO)

G54.1+0.3: Results

- Hint of Signal in 07 Moonlight data.
- 2008 Follow-up yields a 7σ detection in 36 hours
- Location compatible with pulsar
  - Extension consistent with point source.

Significance Map

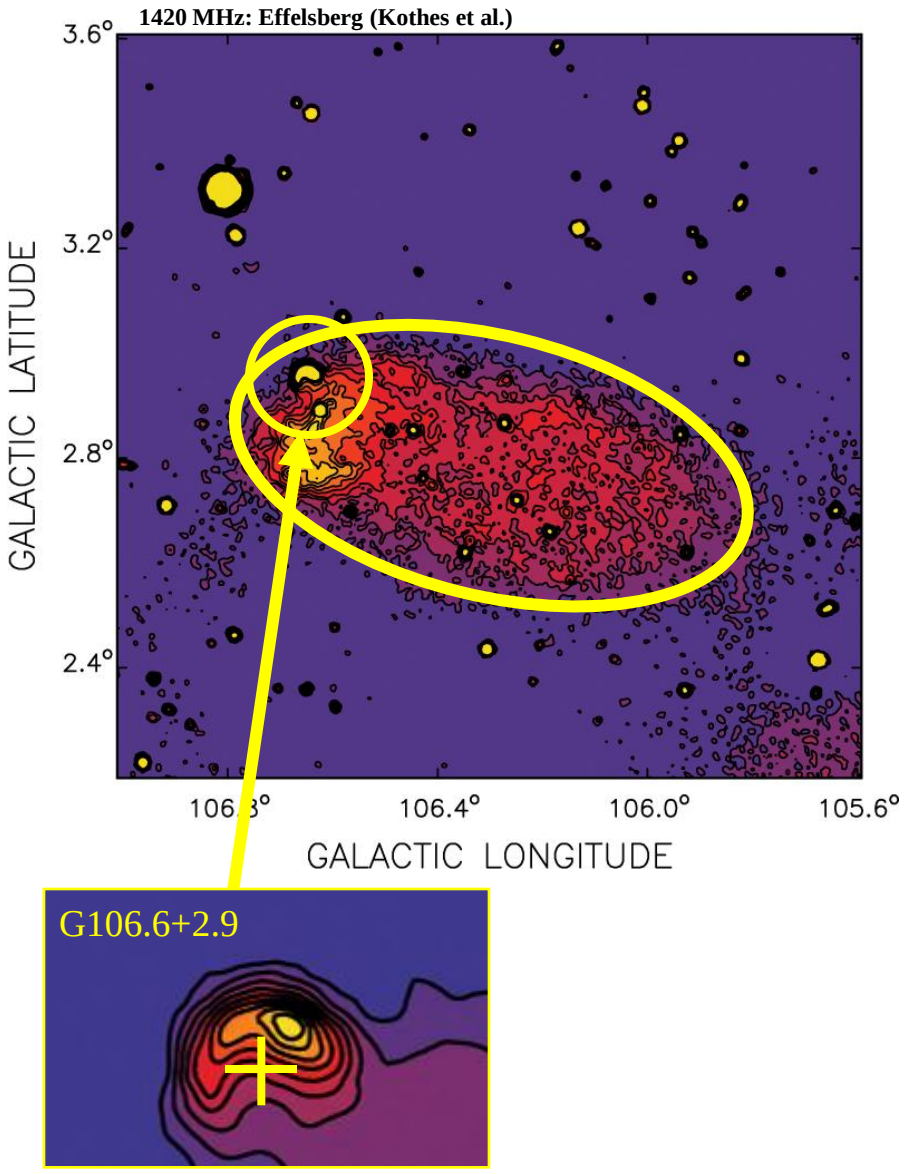




- Gamma-ray Spectrum:
  - Flux (> 1 TeV) ~ 2.5% Crab
  - Index ~ 2.4 0.2_{stat} 0.3_{sys}
  - Efficiency: $\eta_\gamma = 0.17$

Acciari et al. ApJL in press

Boomerang/PSR J2229+6114: Motivations



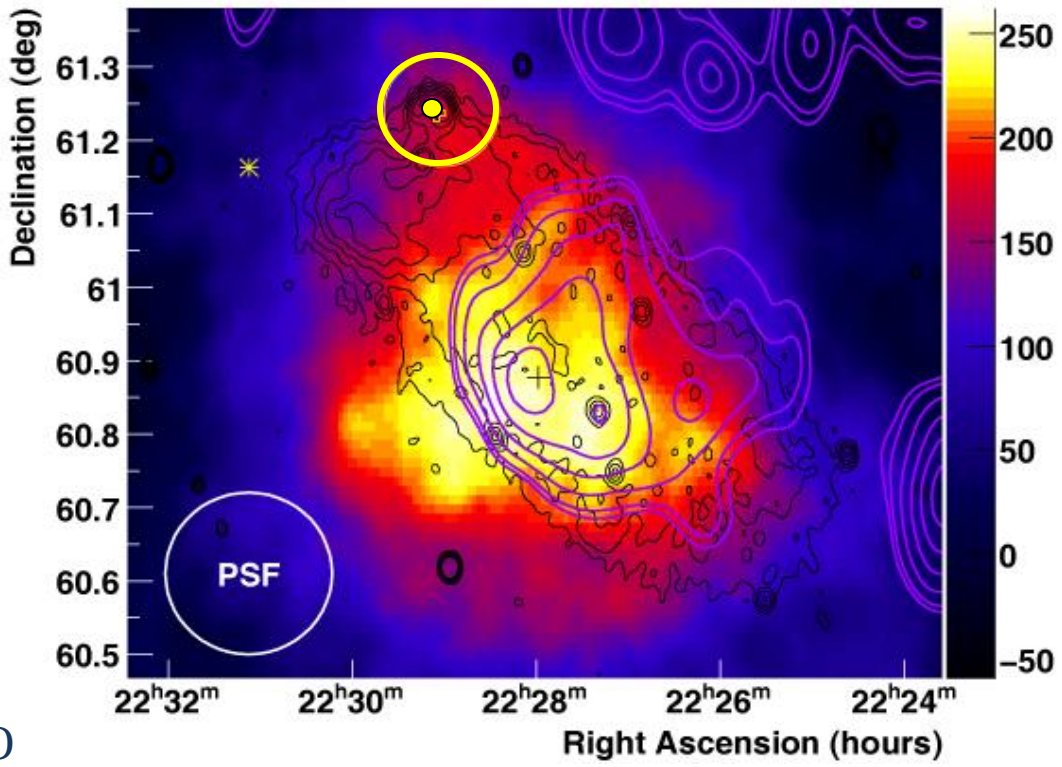
- Energetic pulsar + wind nebula discovered in the error box of source 3EG J2227+6122.
  - Age ~ 10,000 years
  - E-dot = 2.2×10^{37} erg/s
  - Distance ~ 800 pc (Kothes et al)
  - Likely part of the larger SNR G106.3+2.7
- On Fermi/LAT Bright Source List
- Emission at ~35 TeV reported by Milagro near former "C4" location

Boomerang/PSR J2229+6114: Results

- Observations made in 2008 resolve TeV emission overlapping the radio shell of G106.3+2.7
  - 7.3σ detection in 33 hours (6.0 post-trials)

- TeV emission is extended
  - Spans a 0.4 x 0.6 region
  - Peak is 0.4 away from PSR
  - Overlaps with region of high CO density

Multiwavelength Excess Map

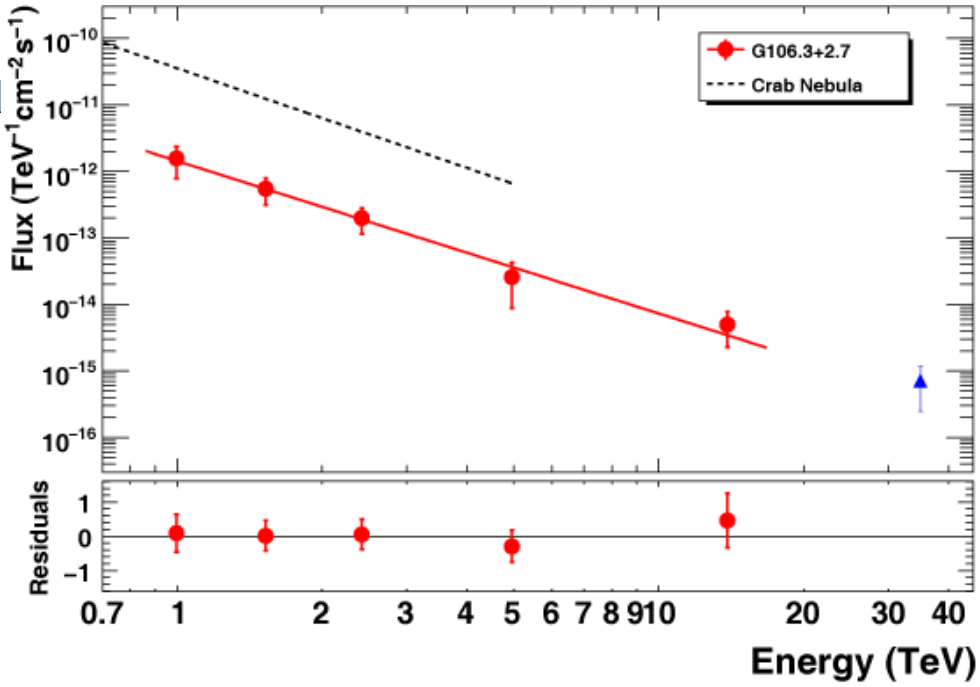


Black – Radio (DRAO)
Circle – FGST Error Box
Dot – Pulsar Position
Purple - ^{12}CO Emission (FCRAO)

Acciari et al. ApJL 703 (2009)

Boomerang/G106.6+2.9: Results II

- Energy Spectrum
  - Integrate over 0.32 radius centered on emission peak
  - Flux above 1 TeV is ~5% of the Crab Nebula
  - Well fit by pure power law
    - Index ~ 2.3 0.3_{stat} 0.3_{sys}



- Consistent within errors with Bednarek and Bartosik PWN Model (J Phys G 31, 2005)

- Extension of spectrum is consistent within errors with Milagro point at 35 TeV
  - Favors hadronic origins?

Acciari et al. ApJL 703 (2009)

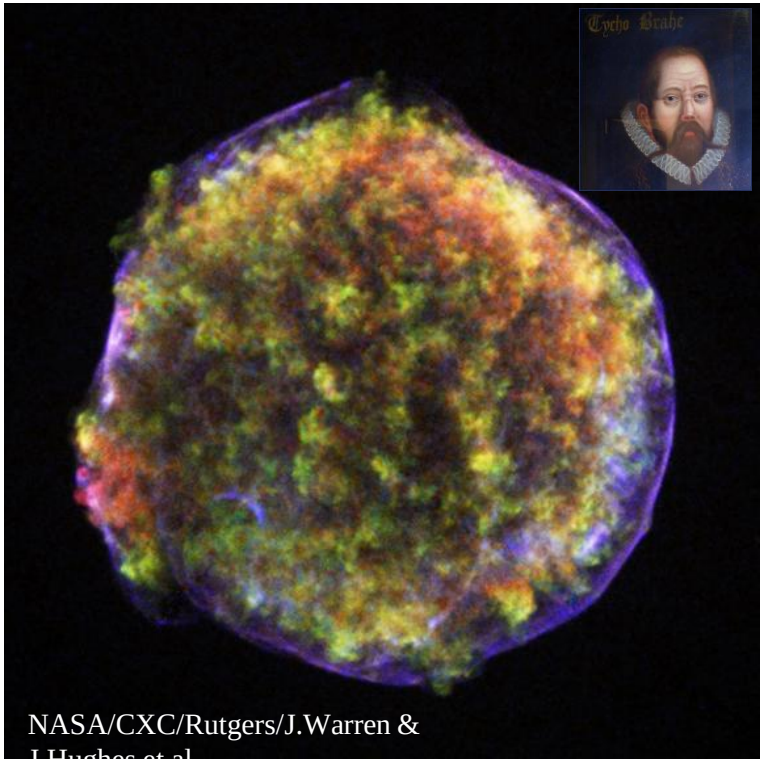
Tycho (G120.1+1.4)

- Remnant of a Type Ia Supernova event of 1572
  - Size: ~8 arcminutes
  - Distance: 2.5 kpc – 5.0 kpc
  - Bright x-ray rims and filaments interpreted as evidence for electrons up to ~10 TeV
  - MWL Expansion Studies suggest entry to Sedov Phase
    - Slower expansion to east possibly due to interactions with molecular cloud

  - Detailed x-ray morphology studies suggest efficient hadronic particle acceleration (Warren et al. 05)

Tycho (G120.1+1.4)

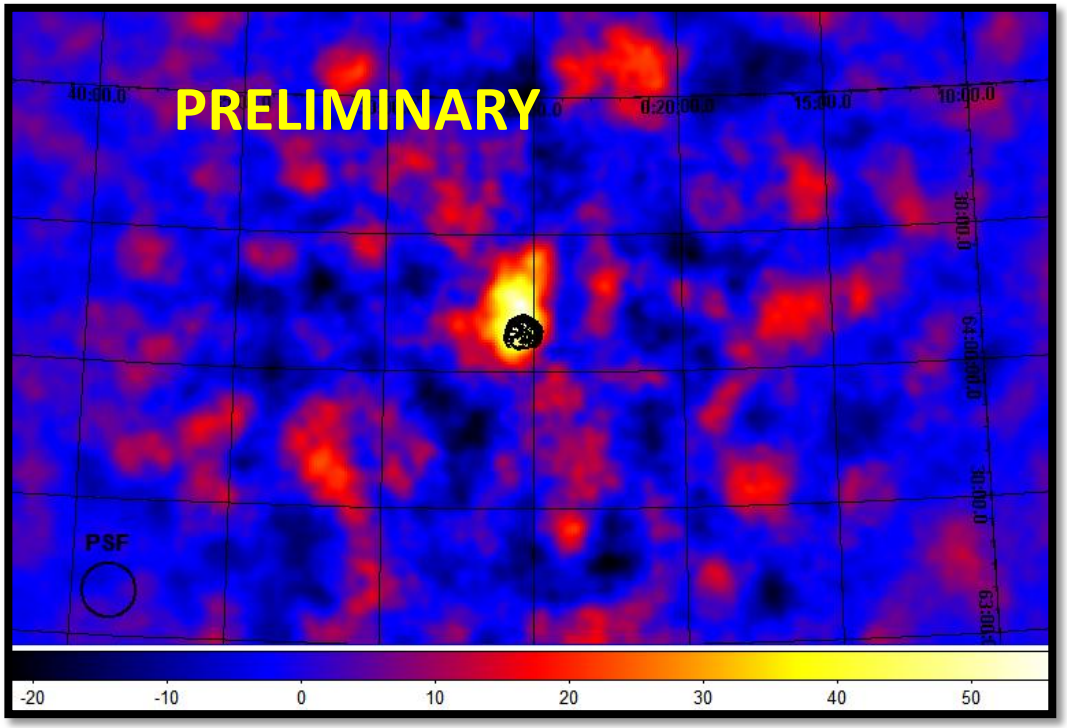
- GeV Observations
  - No Detection by EGRET
  - No 1FGL sources within 3deg
- Past TeV Observations
  - Limits from Whipple, HEGRA, MAGIC
    - Best limit: MAGIC centered pt src: J(>1 TeV) < 1.7% Crab [3σ]
- VERITAS Observations
  - 67 hours from 2008 and 2010 (after quality cuts)
  - Mean zenith – 38 deg



Tycho (G120.1+1.4)

- VERITAS Detection!
  - 5.7σ pre-trials, 5σ post-trials (scan over area x2 area of remnant + 2 cut-sets)
  - Peak Significance located close to molecular cloud – possible interaction?
  - No strong statistical evidence for angular extension
  - Flux Level above 1 TeV: ~1% Crab

Smoothed TeV Excess Map



Black – X-Ray (Chandra)
Purple - ^{12}CO Emission (FCRAO)

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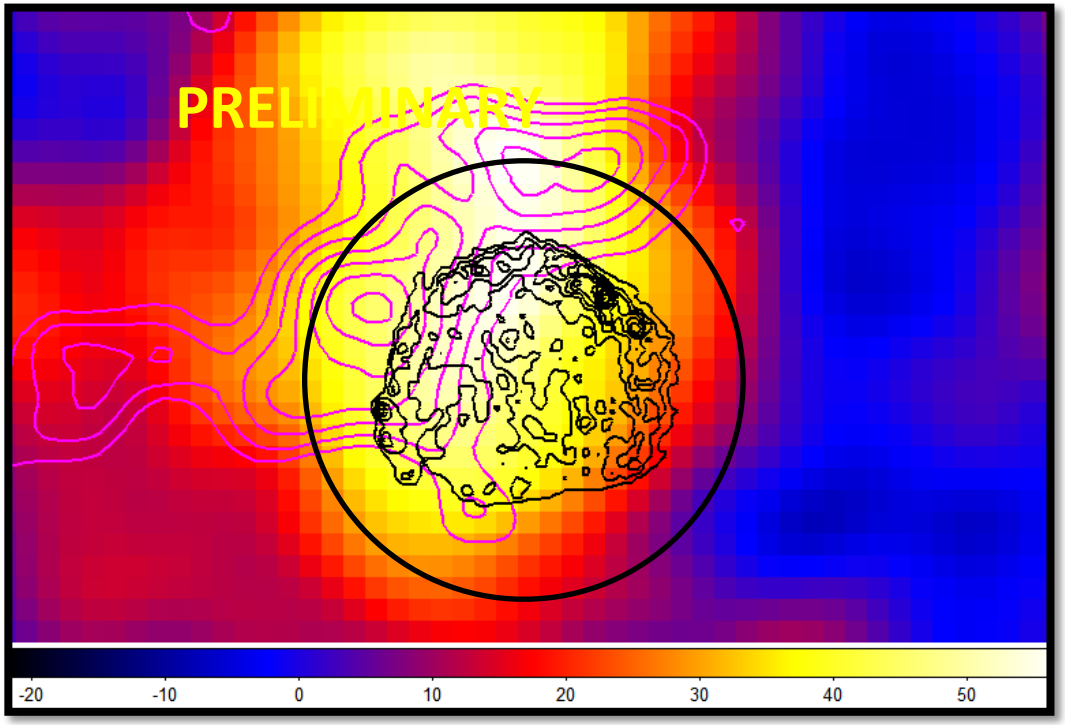

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Summary

- VERITAS has made detections of several galactic objects, including several "new" TeV emitters
  - **γ-Cygni: (Jamie – Monday) New TeV-emitting SNR discovered in sky survey, busy region!**
  - **Cas A: Bright young remnant, pointlike detection in VERITAS and Fermi**
    - **Hadronic models favored. No clouds!?**
  - **IC443: Classic MC/SNR interaction, extended detections by Fermi, VERITAS**
    - **Fermi+VERITAS data well fit by hadronic model**
  - **G54.1+0.3/PSR J1930+1852: High E-dot PWN with possible molecular cloud**
    - **Detection consistent with point source at pulsar location**
  - **G106.3+2.7 (Boomerang): Extended emission, overlapping CO cloud, well away from PWN**
    - **If associated with MGRO 2229+611, hadronic origins may be favored.**
  - **Tycho: Historical Type Ia, several signs of particle acceleration**
    - **Weak detection peaks near associated molecular cloud**
- Questions:
  - **Does the hard spectrum of G106.3+2.7 / MGRO 2229+611 really favor hadronic origins?**
  - **Which of these will teach us the most if we add another 50-100 hrs observation?**
  - **Are there objects missing from this list whose absence is a surprise? (Andy?)**